JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 107, NO. D3, 10.1029/2001JD000589, 2002

How linear is the Arctic Oscillation response to greenhouse gases?

Nathan P. Gillett and Myles R. Allen
Department of Physics, University of Oxford, Oxford, UK

Ruth E. McDonald and Catherine A. Senior
Hadley Centre, Met Office, Bracknell, UK

Drew T. Shindell and Gavin A. Schmidt
NASA Goddard Institute for Space Studies, New York, New York, USA

Received 5 March 2001; revised 3 August 2001; accepted 9 August 2001; published 2 February 2002

[1] We examine the sensitivity of the Arctic Oscillation (AO) index to increases in greenhouse gas concentrations in integrations of five climate models (the Hadley Centre coupled models (HadCM2 and HadCM3), the European Centre/Hamburg models (ECHAM3 and ECHAM4), and the Goddard Institute for Space Studies stratosphere-resolving (GISS-S) model) and in the National Centers for Environmental Prediction reanalysis. With the exception of HadCM2 all the models show a significant positive AO response to greenhouse gas forcing, but in the models lacking a well-resolved stratosphere that response is smaller than observed. In these models the AO index is linearly dependent on the radiative forcing, even up to $\sim$20 times current CO_2 levels. By contrast, the GISS-S stratosphere-resolving model shows an AO response comparable to that observed, but the sensitivity of the model to further increases in forcing is reduced when CO_2 levels exceed $\sim$1.5 times preindustrial values. It has been suggested that greenhouse gas forcing results in the equatorward deflection of planetary waves, which leads to a cooling and strengthening of the polar vortex and hence an increase in the surface Arctic Oscillation. In the observations the number of sudden warmings has reduced dramatically, consistent with this planetary wave effect, leading to a large mean cooling of the vortex. However, neither the GISS-S nor the HadCM3 models are able to reproduce the observed temperature changes, suggesting that this explanation for the impact of the inclusion of a stratosphere in the model may be incomplete. *INDEX TERMS:* 1610 Global Change: Atmosphere (0315, 0325); 1620 Global Change: Climate dynamics (3309); 3362 Meteorology and Atmospheric Dynamics: Stratosphere/troposphere interactions; *KEYWORDS:* Arctic Oscillation; greenhouse gas; AO; GCM; CO2

1. Introduction

[2] The Arctic Oscillation was defined by *Thompson and Wallace* [1998] as the first empirical orthogonal function of Northern Hemisphere winter monthly sea level pressure and may be regarded as a hemispheric variant of the North Atlantic Oscillation (NAO) [*Walker and Bliss*, 1932]. The positive phase of the Arctic Oscillation is associated with decreased surface pressure over the Arctic and increased surface pressure over the northern subtropical oceans. *Thompson and Wallace* [1998] drew attention to the trend in the index they define, and since then several studies have examined this mode in general circulation models (GCMs), analyzing both its natural variability and its changes in anthropogenically forced integrations. These studies have arrived at differing conclusions regarding the mode's response to forcing and the realism of that response.

[3] *Thompson et al.* [2000] test the significance of the observed upward trend in the Arctic Oscillation (AO) over 30 years for each month and find it to be significant from January to March when tested against a red noise model. This trend in the AO and NAO has been found to be significant compared to control variability in the second Hadley Centre coupled model (HadCM2) [*Osborn et al.*, 1999; *Gillett et al.*, 2000]. Since the observed zonalization trend cannot be accounted for by modeled internal variability, many studies have examined other possible explanations, in particular greenhouse gas forcing (Table 1). Generally, the models used in these studies show an increase in the AO index in response to greenhouse gas increases, with the exception of HadCM2, the Goddard Institute for Space Studies troposphere-only (GISS-T) model and the National Center for Atmospheric Research climate system model (CSM). The AO and NAO responses are consistent in most cases: Any differences are likely to be due to systematic changes in position of the NAO centers of action in response to forcing [*Ulbrich and Christoph*, 1999]. *Shindell et al.* [1999] compared their modeled trend with that observed and conclude that while the stratosphere-resolving GCM shows a realistic trend, the troposphere-only model exhibits an insignificant and unrealistically small trend. However, they base their trend estimate on several decades including the future part of their integration, so the comparison with observations is not a direct one. Observed changes in the circulation of the winter stratosphere are analyzed by *Gillett et al.* [2001]. They find a statistically significant change in both the mean and the shape of the distribution of the AO index in the stratosphere in January, with fewer sudden warmings in the second half of the record but only a small change in the maximum vortex strength.

[4] In January the Arctic polar stratosphere is warmed from its radiatively determined state by dynamical heating due to wave driving of the meridional circulation by upward propagating

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Table 1. Arctic Oscillation and North Atlantic Oscillation Response to Greenhouse Gases[a]

Model	AO Response	NAO Response	Source
HadCM2	NC	decrease	1, 2, 3
HadCM3	increase	increase	4
ECHAM3	increase	increase	5, 6
ECHAM4	increase	increase	2, 7, 8
CCCma	increase	NC	9
GISS-S	increase		10, 11
GISS-T	NC		10, 11
CSIRO	increase		12
CCSR	increase		12
NCAR-CSM	NC		8

[a]NC indicates no significant change. Sources are the following: 1, *Gillett et al.* [2000]; 2, *Zorita and González-Rouco* [2000]; 3, *Osborn et al.* [1999]; 4, R. McDonald (personal communication, 2000); 5, H. Paeth (personal communication, 2000); 6, *Paeth et al.* [1999]; 7, *Ulbrich and Christoph* [1999]; 8, *Robertson* [2001]; 9, *Fyfe et al.* [1999]; 10, *Shindell et al.* [1999]; 11, *Shindell et al.* [2001]; 12, E. Zorita (personal communication, 2000). GISS-S denotes the 23-level GISS model with a model top at 0.002 hPa, and GISS-T denotes the 9-level GISS model with a model top at 10 hPa. Note that the CCCma model was additionally forced with changes in sulphate aerosol.

planetary waves. Strong disturbances are known as sudden warmings. However, in the winter, dynamical effects do not act to cool the vortex, so the undisturbed vortex strength is limited to the radiatively determined state [*Shine*, 1987], leading to the observed skewness in the distribution of polar temperatures [*Labitzke*, 1982; *Gillett et al.*, 2001]. As greenhouse gases warm the tropical upper troposphere and cool the polar stratosphere, we expect the meridional temperature gradient in the region of the tropopause to increase, leading directly to a slight strengthening of the stratospheric vortex from the thermal wind relation. Furthermore, the changed zonal wind profile could also act to deflect upward propagating planetary waves equatorward, so that they heat the vortex less, reducing the number of sudden warmings and increasing the mean vortex strength [*Rind et al.*, 1998]. This effect may then act as a positive feedback on the mean vortex strength [*Shindell et al.*, 1999]. However, as the forcing further strengthens, all the planetary waves may eventually be deflected away from the pole, so that the vortex approaches a radiatively determined state [*Shindell et al.*, 2001]. This response mechanism would then have saturated, and the only influence of further increases in forcing on vortex strength would then be through the direct radiative effect, which is weaker. If the downward influence discussed by *Baldwin and Dunkerton* [1999] is also important on longer timescales, as *Hartmann et al.* [2000] conclude, then we might also expect an influence on the tropospheric AO. *Shindell et al.* [2001] show evidence of such a saturation of response in the surface AO in the stratosphere-resolving version of the GISS model.

[5] On the basis of *Shindell et al.*'s [1999] findings we might expect a change in sensitivity of the Arctic Oscillation index to increases in forcing as the planetary wave effect saturates, that is, when all the planetary wave flux is deflected equatorward. However, since forcing due to greenhouse gases has not been increased linearly in many of the experiments included in Table 1, this is hard to assess. *Ulbrich and Christoph* [1999] compared the evolution of a regionally based NAO index (avoiding the problems associated with a station-based index) with the radiative forcing at the tropopause associated with greenhouse gas changes and found that the two were almost exactly proportional in the fourth European Centre/Hamburg model (ECHAM4). We assess the extent to which this relationship holds in other models and in observations. We also examine probability density functions (PDFs) of the AO index to look for "regime" changes, of the type discussed by *Palmer* [1999] and *Corti et al.* [1999], and for further evidence of any nonlinearities in the response to forcing.

2. Arctic Oscillation Response to Greenhouse Gas Forcing

2.1. HadCM3

[6] HadCM3 is a coupled ocean-atmosphere general circulation model with a horizontal resolution of $2.5° \times 3.75°$ and 19 levels extending up to 10 hPa [*Gordon et al.*, 2000; *Pope et al.*, 2000]. We examine the Arctic Oscillation index in several runs of HadCM3 forced with changing greenhouse gas concentrations only. After deriving indices as described in Appendix A, we plotted the AO index against a model-based reconstruction of the radiative forcing at the tropopause for all available greenhouse gas forced integrations of HadCM3 (Figures 1a and 1b). Integrations labeled 2% and 1% have a prescribed constant rate of increase of CO_2 of 2% and 1% per annum (pa), respectively. Integrations labeled IS92a and SRESB2 have greenhouse gas changes prescribed according to the Intergovernmental Panel on Climate Change IS92a and SRESB2 [*Stott et al.*, 2000] scenarios. The 2% pa runs have $\sim$20 times preindustrial CO_2 concentrations at the end of the period plotted. One of these runs was continued for an additional 50 years to $\sim$50 times preindustrial CO_2 levels, and toward the end of this period the AO stopped increasing, but these data were disregarded because the model response is thought to become unrealistic at these very high forcings (R. Thorpe, personal communication, 2000). Note first that over the range of forcings plotted, the AO appears to increase linearly with the forcing in each run. Second, the response appears to be independent of the rate of increase in forcing. This result is supported by the calculated gradients, shown in Figure 1c, which are all consistent with one another, although three are individually consistent with zero. These SRESB2 integrations were halted at 2000; thus the range of greenhouse gas forcing in each run is smaller, and uncertainties in the sensitivity are larger. Overall, the AO response to greenhouse gas forcing in this model on decadal timescales appears to be dependent only on the instantaneous forcing and not on its rate of change. Further, the change is linear, with the same AO change for a given increase in forcing at preindustrial CO_2 levels as at $\sim$20 times those levels. A similar result was found for runs of the third European Centre/Hamburg model (ECHAM3) [*Voss et al.*, 1998] with two different forcing histories (Figure 2). This result contrasts with that of *Shindell et al.* [1999], who found a change in AO sensitivity in their stratosphere-resolving model at less than 2 times preindustrial CO_2 levels. The linearity of the response in HadCM3 suggests that Arctic Oscillation changes in this model are induced by a component of the climate system which itself responds linearly to changes in radiative forcing. The independence of the response from the rate of change of forcing on decadal timescales suggests that slow ocean-atmosphere coupling is not involved.

2.2. Comparison With Observations and Other Models

[7] In order to assess the realism of the results for HadCM3 we compared the calculated AO sensitivity first with that of the real atmosphere, using observations (1948–1998) and, second, with other coupled GCMs. Figure 3a shows the AO sensitivity to radiative forcing at the tropopause in HadCM3 (a weighted mean of the sensitivities shown in Figure 1c) along with that in four other GCMs and in the observations. Uncertainty ranges on the model sensitivities were estimated using control variability, and the uncertainty range on the observed sensitivity was estimated using HadCM3 control. The comparison with the observations should be viewed with some caution, because many other forcings also influence the observed AO [see, e.g., *Shindell et al.*, 2001]. The solid bar shows the observed AO sensitivity calculated with respect to the radiative forcing at the tropopause due only to greenhouse gases, reconstructed using HadCM3. Anthropogenic sulphate aerosol, ozone changes, changes in solar irradiation, and volcanic aerosol all alter the global temperature field in different ways from greenhouse gases, and hence accounting for their influence on the

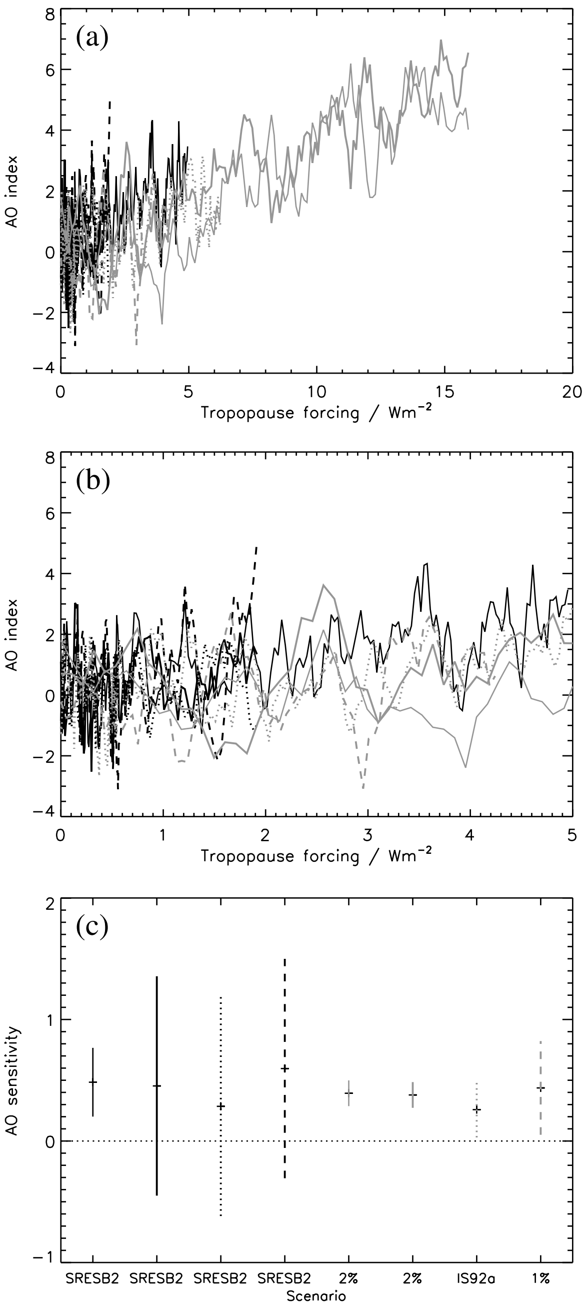

Figure 1. (a) The 5-year smoothed Arctic Oscillation (AO) index plotted against the radiative forcing at the tropopause in eight scenario runs of the third Hadley Centre coupled model (HadCM3) with changed greenhouse gas concentrations only. A pure doubling of CO_2 corresponds to a tropopause forcing of 3.74 W m^{-2} in HadCM3, and this forcing is predicted to occur in ~2040 due to all well-mixed greenhouse gases in the IS92a scenario. (b) An enlargement of the part of panel a showing forcing between 0 and 5 W m^{-2}. (c) The gradients of the associated unsmoothed lines, with their 5–95% confidence ranges, evaluated from control variability. Note that all the gradients are consistent with each other: The response is linear in the forcing and does not saturate.

AO by their net radiative forcing at the tropopause is not necessarily physically reasonable. However, a similar sensitivity is obtained with respect to a reconstruction of total radiative forcing at the tropopause if volcano years are disregarded (shaded bar). Years with an optical depth due to volcanic aerosol >0.04 were masked out (1963–1964, 1969, 1982–1983, and 1991–1993), since volcanic eruptions have a strong influence on the stratospheric temperature field and hence on the AO due to a mechanism very different from that of greenhouse gas influence [*Graf et al.*, 1994]. Subject to these caveats, we note that the best estimate of observed AO sensitivity to greenhouse gas forcing is much higher than that of HadCM3, although the sensitivities are marginally consistent. Figure 3b shows the sensitivity of a station-based NAO index to the radiative forcing at the tropopause, and conclusions are similar, although the observed sensitivity is here marginally consistent with zero. Likewise, Figure 3c shows the sensitivity of the AO index with respect to winter mean Northern Hemisphere surface temperature, and it may be seen that the relative sensitives are very similar to those with respect to radiative forcing at the tropopause. This diagnostic increases linearly with the radiative forcing, so this is to be expected. However, since the Arctic Oscillation also causes changes in winter mean Northern Hemisphere surface temperature [*Thompson et al.*, 2000], the direction of causality is less clear in this case, so we concentrate on the sensitivities with respect to radiative forcing.

[8] ECHAM3 and ECHAM4 [*Bacher et al.*, 1998] both show a positive AO sensitivity consistent with that of HadCM3. These models also show a linear dependence of the AO on the radiative forcing. By contrast, HadCM2 [*Johns et al.*, 1997] shows no significant AO response to greenhouse gas forcing and a slightly negative NAO response. This is consistent with other published findings [*Osborn et al.*, 1999; *Gillett et al.*, 2000]. However, HadCM2 shows a pattern of surface pressure change under increased greenhouse gas conditions very different from HadCM3 [*Williams et al.*, 2001], and other GCMs, with a large decrease in sea level pressure (SLP) over the northern Pacific, in contrast to the

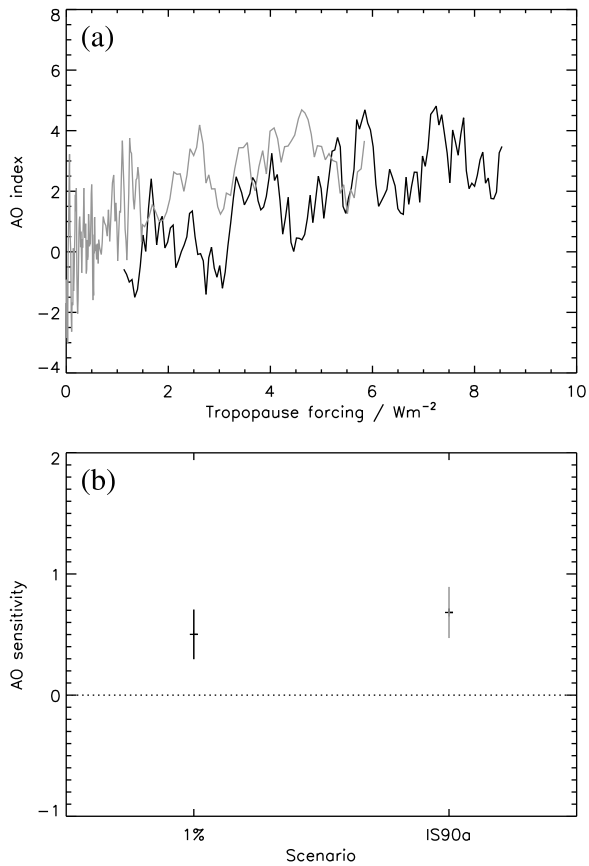

Figure 2. As Figure 1 but for two greenhouse gas forced integrations of the third European Centre/Hamburg model (ECHAM3).

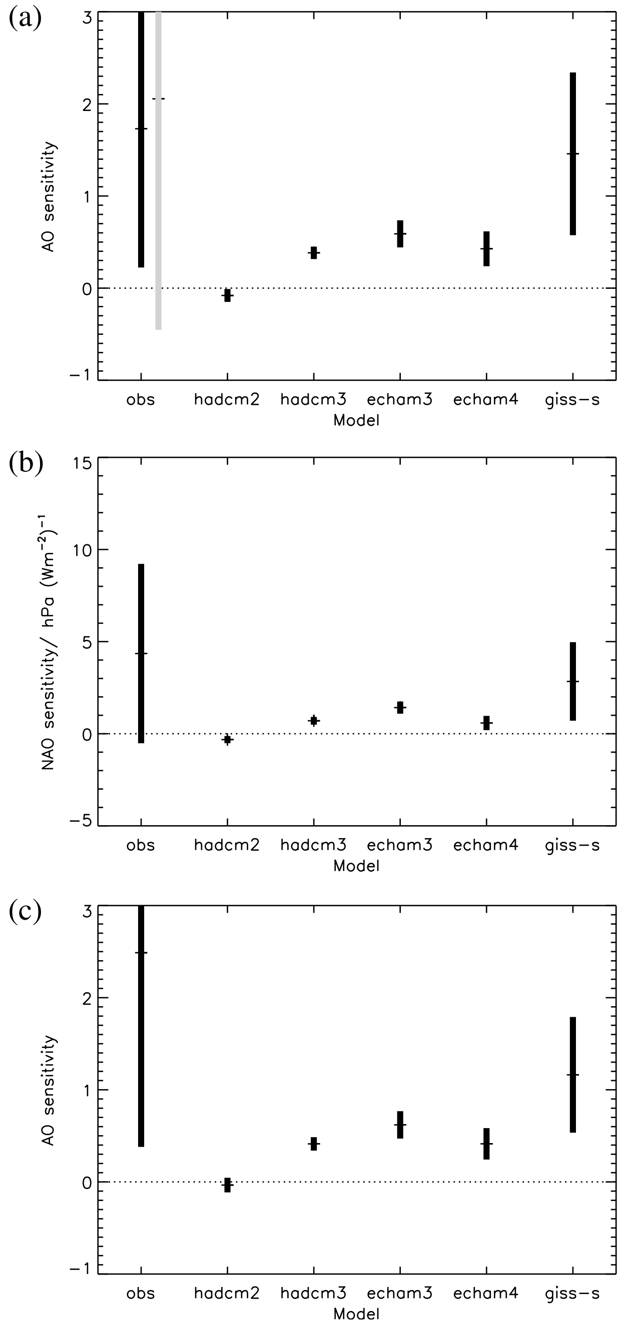

Figure 3. (a) The mean sensitivity of the AO index to net radiative forcing at the tropopause due to greenhouse gases in four general circulation models (GCMs) and observations (solid bars). The shaded bar shows the mean sensitivity of the observed AO with respect to a reconstruction of total net forcing at the tropopause. Years with a mean volcanic aerosol optical depth >0.04 were masked out. (b) The mean sensitivity of the NAO index (Azores-Iceland sea level pressure) to tropopause forcing. (c) The mean sensitivity of the AO to Northern Hemisphere winter mean surface temperature. The associated 5–95% confidence interval is shown in each case, based on control integrations.

increase seen in HadCM3. *Williams et al.* [2001] showed that the difference in the North Pacific SLP response in HadCM2 is due to a larger surface warming in the tropics than in HadCM3. This difference in the warming pattern is due to different cloud feedback effects arising from differences in the boundary layer scheme and critical relative humidity for cloud formation.

[9] All the GCMs so far discussed have poor stratospheric resolution, and they all show a much lower sensitivity than the best guess value for the observations. However, *Shindell et al.* [1999] report a realistic AO response in a stratosphere-resolving GCM coupled to a thermodynamic ‘‘slab’’ ocean (GISS-S) [*Rind et al.*, 1998]. They also note that the sensitivity to forcing appears to vary with time, the response saturating after ~60 years (~1.5 times preindustrial CO_2) [*Shindell et al.*, 2001]. Thus, in order to best compare the sensitivity with observations, we focused our attention on the 60-year period prior to this saturation. The AO and NAO sensitivities for this model are included in Figure 3. In all cases the best guess sensitivity is greater than for the GCMs with poor stratospheric resolution and is closer to the best guess observed sensitivity. Our confidence in this estimate is limited by the single ensemble member available and the short period considered before the response saturated. An analysis of Arctic Oscillation changes in two other greenhouse gas forced integrations of GISS-S also incorporating stratospheric ozone depletion gave sensitivities somewhat lower than that of the greenhouse-gas-only integration. This difference may be partially attributable to cooling from extrapolar ozone depletion, which weakens the latitudinal temperature gradient in the lower stratosphere. However, since this effect is likely to be small, these results suggest that the true sensitivity of the GISS-S model may be toward the lower end of the confidence regions shown. Nonetheless, these findings support the hypothesis that a well-resolved stratosphere results in a more realistic AO response to greenhouse gas forcing.

3. Distribution of the AO index

3.1. Tropospheric Changes

[10] Several authors have suggested that climate change may manifest itself as a change in the occupation frequencies of preexisting climate ‘‘regimes’’ [*Corti et al.*, 1999; *Palmer*, 1999]. Such ‘‘regimes’’ would be expected to give rise to multiple maxima in the PDF of the system, whose centroids would remain stationary as their associated occupation probabilities changed in response to forcing. While *Gillett et al.* [2001] found no evidence of multiple maxima in the PDF of the observed surface Arctic Oscillation and no corresponding change in its shape over the length of the observed record, it could be the case that changes in the shape of the PDF might only manifest themselves when the atmosphere is exposed to a larger change in forcing. A change in the shape of the PDF could be a better indicator of any nonlinearity in the modeled response to forcing than a change in the sensitivity of the mean. Figure 4 shows histograms of daily winter AO indices for each half of one of the 2% pa CO_2 increase runs shown in Figure 1. First, the PDFs for each half of the run are clearly unimodal, as for PDFs of the observed AO index [*Gillett et al.*, 2001]. Second, the shape of the PDF has not changed. This result was verified using a Kolmogorov-Smirnov test in the way described by *Gillett et al.* [2001]. These results strengthen our conclusion that the surface response of the Arctic Oscillation in HadCM3 is linear. This is consistent with results for the observations [*Gillett et al.*, 2001], although the strength of our conclusions in this case is limited by the shortness of the record. Nonetheless, no multimodality of the type discussed by, for example, *Palmer* [1999] and *Corti et al.* [1999] is seen in HadCM3.

3.2. Stratospheric Changes

[11] In sections 2.1 and 3.1 we showed that the Arctic Oscillation response of HadCM3 to greenhouse gas forcing is linear, both in terms of changes in the mean and distribution of the AO index. While this linearity in the response at the surface is not in disagreement with the observations, the sensitivity to forcing is

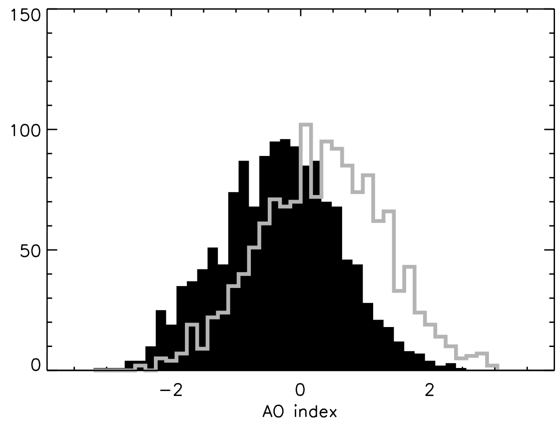

Figure 4. Histograms of 5-day mean AO index for December–February from the first (solid) and second (shaded line) halves of a 154-year integration of HadCM3 subject to a 2% per annum increase in CO_2.

considerably less than the best estimate of that of the real atmosphere. In order to better understand this difference we now examine the behavior of HadCM3's stratosphere. *Gillett et al.* [2001] found that the observed strength of the winter polar vortex has a skewed distribution and that the shape of this distribution has changed over the past 40 years. They conclude that this nonlinearity in the stratospheric response to forcing manifests itself most in January, when the vortex is coldest, and close to 70 hPa, where temperatures are closest to the radiatively determined limit. While this limit affects the geopotential height field indirectly via the thermal wind relation, its effect is most clearly seen in polar stratospheric temperatures. Hence we examine the January mean 50-hPa North Pole temperature (the closest available model data) in a 300-year section of the control integration of HadCM3 and compare its distribution with that of the equivalent National Centers for Environmental Prediction (NCEP) data (Figure 5). The mean vortex temperature is somewhat too high (the model does not have a "cold pole"), its variance is somewhat too low, and the shapes of the distributions are very different. The positive skewness in equivalent NCEP daily data was discussed in some detail by *Gillett et al.* [2001], who found that the minimum of the distribution lies close to the radiatively determined limit. Such an effect is clearly not apparent in HadCM3, perhaps partly because of the model's warm bias in this region. Overall, these results suggest that stratospheric processes are poorly resolved in HadCM3. However, this distribution is no better simulated in GISS-S (Figure 5c), suggesting that this model too lacks realism in its simulation of stratospheric processes, perhaps partly because of its coarse horizontal resolution of $8^\circ \times 10^\circ$.

[12] Figure 6 shows how the distribution of January polar vortex temperatures has changed between the periods 1958–1978 and 1979–1999. While the NCEP data show a cooling of 3.0 K between the periods shown, HadCM3 cools by only 0.6 K, and in the single integration of GISS-S available, the mean vortex temperature actually increases slightly, although this change is not significant. (Over the whole integration, temperatures in this region do decrease somewhat in GISS-S [*Shindell et al.*, 1998]). Thus, while the observations indicate that the vortex has cooled somewhat, neither model shows a statistically significant cooling over the same period. Since these GCMs do show a small AO increase over this period, these results suggest that the observed increase in the Arctic Oscillation may not be entirely due to stratospheric cooling.

[13] Sudden warmings are caused by downward motion within the vortex induced by planetary waves propagating up from the troposphere. If these waves are deflected equatorward in the upper troposphere and lower stratosphere by the zonal wind profile associated with a changed meridional temperature gradient, then we might expect the impact to be largest on warm events, which is consistent with our NCEP results. This effect is more clearly seen in daily data [*Gillett et al.*, 2001]. We use monthly data here because equivalent daily data are not available for HadCM3. However, if this planetary wave deflection mechanism is responsible for the observed changes, then it is clearly not influencing polar stratospheric temperatures in the same way in the GCMs. This suggests that the hypothesized planetary wave feedback affect may not be the only process responsible for the difference between the AO sensitivities of the stratosphere-resolving and

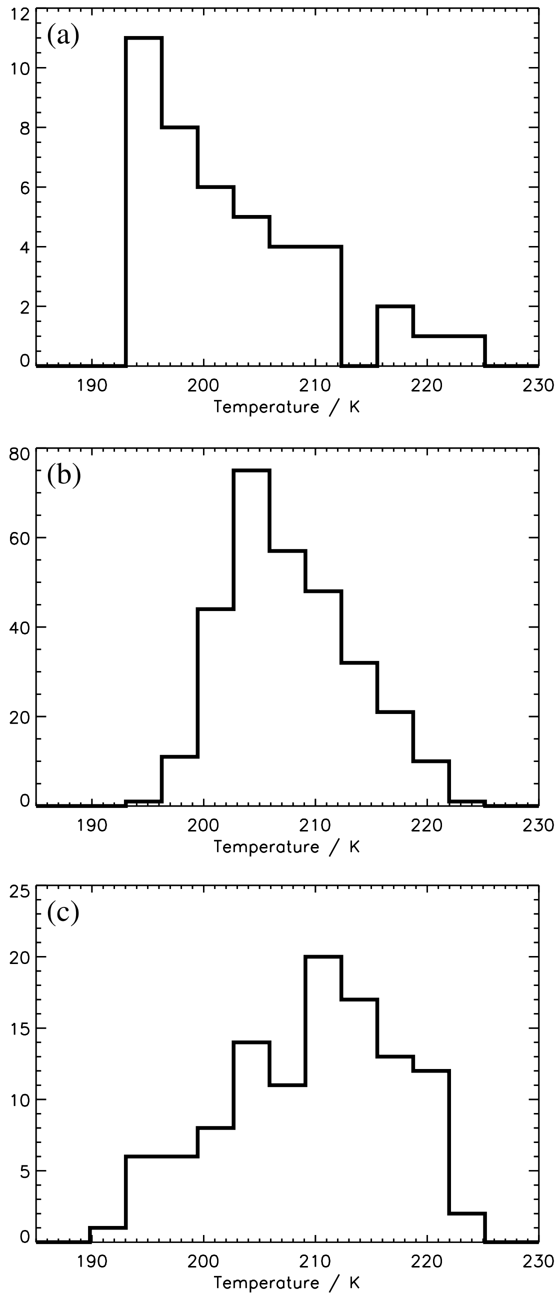

Figure 5. Histograms of January mean North Pole 50-hPa temperatures from (a) the National Centers for Environmental Prediction (NCEP) reanalysis (1958–1999), (b) 300 years of HadCM3 control integration, and (c) 30- to 100-hPa mean North Pole temperature from a climate change integration of the Goddard Institute for Space Studies (GISS) stratosphere-resolving model.

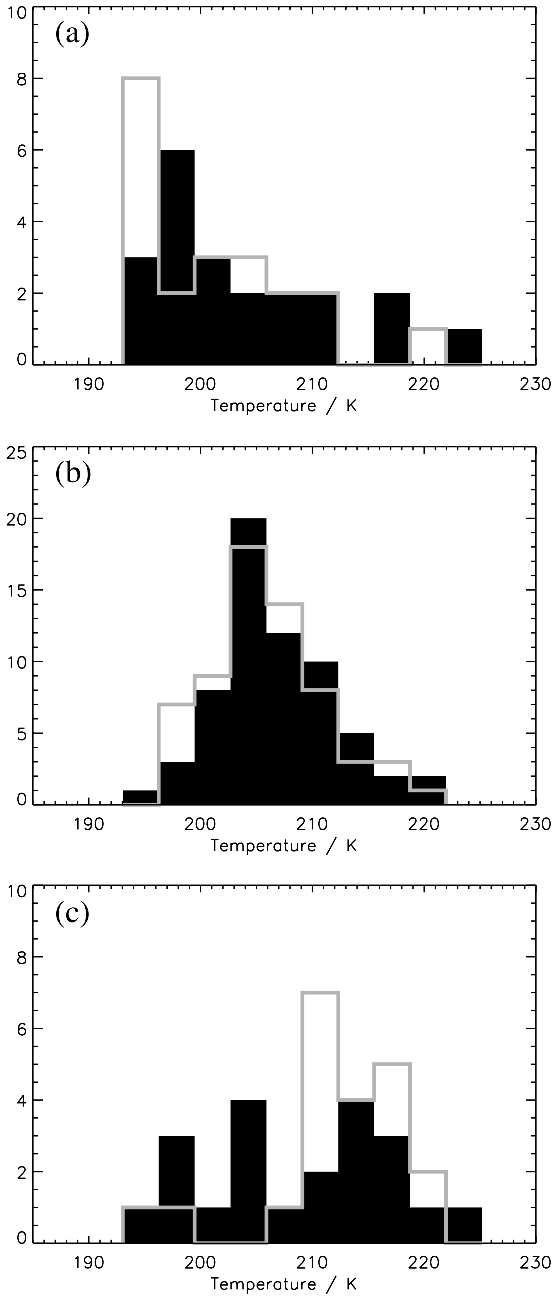

Figure 6. Histograms of January mean North Pole 50-hPa temperatures for the period 1958–1978 (solid) and 1979–1999 (shaded line) from (a) the NCEP reanalysis and (b) a three-member ensemble of HadCM3 integrations forced with observed changes in greenhouse gases. The mean change in NCEP data is −3.0 K. The mean change in HadCM3 is −0.6 K. (c) The change in 30- to 100-hPa mean North Pole temperature over the same period from a single integration of GISS-S also forced with observed changes in greenhouse gases.

non-stratosphere-resolving GCMs. Thus it is important to verify the results of *Shindell et al.* [1999] for other models.

4. Conclusions

[14] Four of the five GCMs studied (HadCM3, ECHAM3, ECHAM4, and GISS-S) show an unambiguously positive Arctic Oscillation and North Atlantic Oscillation response to greenhouse gas forcing, consistent with the hypothesis that the observed upward trend in these indices is anthropogenically induced. The response is linear in the troposphere-only GCMs which show a response to the forcing, most notably in HadCM3, where the response remains linear even up to a CO_2 concentration of ~20 times preindustrial levels. Our analysis suggests that in GCMs with poor stratospheric resolution the Arctic Oscillation does not vary as much in response to a given change in forcing as it has done in the observations and as it does in GISS-S. This is particularly true for HadCM2 which shows no significant AO response to greenhouse gas forcing. These GCMs with poor stratospheric resolution have been used extensively for detection and prediction of anthropogenic climate change [e.g., *Tett et al.*, 1999; *Hegerl et al.*, 1997; *Stott et al.*, 2001]. Since the Arctic Oscillation exerts a large influence on Northern Hemisphere surface temperature, particularly on regional scales [*Thompson and Wallace*, 1998], it is important for these activities that the AO response is realistically simulated.

[15] Although uncertainties in the sensitivity of the observed Arctic Oscillation to external forcing are large, our results suggest that this quantity may be underestimated by most GCMs and that this sensitivity may change as the forcing increases, as it does in GISS-S. This could have implications for climate prediction, particularly on regional scales. However, this nonlinearity in the response is better characterized by a saturation effect rather than a "regime change" of the type discussed by *Palmer* [1999]: We see no multimodality in either modeled or observed PDFs of the Arctic Oscillation. While the Arctic vortex in both HadCM3 and GISS-S cools somewhat over the whole period simulated, changes in polar temperature over the observed period appear to be no more realistic in the stratosphere-resolving model. This suggests that the enhanced AO sensitivity of the GISS-S model may not be entirely due to its ability to simulate cooling of the polar vortex better. We suggest that the results of *Shindell et al.* [1999] should be verified using other models, an issue we pursue elsewhere.

Appendix A: Calculation of AO Indices

[16] Anomalies were taken from the long-term mean of December–February sea level pressure northward of 20°N from 359 years of control integration of HadCM3. The trend in the global area-weighted mean was removed to correct for mass loss in the model, and the anomalies were weighted by the square root of the cosine of latitude so that the corresponding covariance matrix was area-weighted. An empirical orthogonal function (EOF) analysis was then performed, the AO being defined as the first EOF. The trend in total mass and a control climatology were removed from December–February SLP from the observations and each run studied. The resulting anomalies were weighted by the square root of the cosine of latitude, regridded by bilinear interpolation where necessary, and projected onto the control AO pattern to derive AO indices. When intermodel comparisons were made, the HadCM3 AO pattern was used in each case, although results were found to be insensitive to the model used.

[17] **Acknowledgments.** We would like to thank Erich Roeckner, Reinhard Voss, and Reiner Schnur (Max Planck Institute for Meteorology) for providing ECHAM3/4 data and Judith Perlwitz and Hans Graf (MPI) for helpful suggestions and discussion of results. We would also like to thank Simon Tett, John Mitchell, William Ingram, Tim Johns, Jonathan Gregory, Ann Keen, and Robert Thorpe (Hadley Centre) for supplying HadCM2/3 data and discussion of results. We also thank two anonymous reviewers for detailed and helpful comments. N.P.G. was supported by a CASE studentship from the UK Natural Environment Research Council, ref GT04/98/217/AS; M.R.A. was supported by an Advanced Research Fellowship from the UK NERC; R.E.M. and C.A.S. were funded under the public meteorological service research contract; and D.T.S. and G.A.S. gratefully acknowledge the support of NSF grant ATM-00-02267.

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M. R. Allen and N. P. Gillett, Atmospheric, Oceanic and Planetary Physics, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, UK. (atmmra@atm.ox.ac.uk; gillett@atm.ox.ac.uk)

R. E. McDonald and C. A. Senior, Hadley Centre for Climate Prediction and Research, Met Office, London Road, Bracknell, Berkshire RG12 2SY, UK. (remcdonald@meto.gov.uk; casenior@meto.gov.uk)

G. A. Schmidt and D. T. Shindell, NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025, USA. (gschmidt@giss.nasa.gov; dshindell@giss.nasa.gov)